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Impact of Dark Matter Microhalos on Signatures for Direct and Indirect Detection

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Detecting dark matter as it streams through detectors on Earth relies on know-ledge of its phase space density on a scale comparable to the size of our solar system. Numerical simulations predict that our Galactic halo contains an enormous hierarchy of substructures, streams and caustics, the remnants of the merging hierarchy [1, 2] that began with tiny Earth mass microhalos [3–5]. If these bound or coherent structures persist until the present time, they could dramatically alter signatures for the detection of weakly interacting elementary particle dark matter (WIMP). Using numerical simulations that follow the coarse grained tidal disruption within the Galactic potential and fine grained heating from stellar encounters, we find that microhalos, streams and caustics have a negligible likelihood of impacting direct detection signatures implying that dark matter constraints derived using simple smooth halo models are relatively robust. We also find that many dense central cusps survive, yielding a small enhancement in the signal for indirect detection experiments.

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Introduction

In a ΛCDM dominated universe, structure forms by the hierarchical clustering and merging of small density perturbations [6]. Larger systems, such as galaxies form as smaller structures which decouple from the background expansion at earlier times, are cannibalised. Numerical simulations that follow these processes predict that our Galactic halo should contain a vast hierarchy of surviving substructures - the remnants of the entire halo merger tree. The number density of substructures of a given mass M goes as $n \propto M_{subs}^{-1}$ and they span over 15 decades in mass [7]. The smallest, oldest and most abundant are Earth-mass microhalos with a half mass radius of 10^{-2} pc that formed at $z \simeq 26$ [5, 8]. This minimum mass is modulated by the free streaming velocity which is related to the mass of the neutralino [9–11].

Simulations of relatively large subhalos suggest that their gravitational interactions with a disk potential, can lead to a destruction of subhalos at distances closer than 30 kpc [12]. Smaller subhalos form earlier, however, with denser cores, and are therefore the most probable dark matter structures to survive gravitational interactions. A second source of fine grained structure to survive are the numerous caustic sheets and folds that form due to the very high initial phase space density of the cold dark matter particles. These are wrapped in a complex way within all the subsequent structures that form, however in the absence of a heating term, the fine grained phase density would be preserved.

With low internal velocity dispersion and high mean density, both the event rate and the characteristic spectrum of energy deposited by dark matter in direct detection experiments [14] could be affected by any features surviving in the phase space distribution of CDM particles. Direct detection experiments are sensitive to the density and velocity distributions of WIMPs on a scale of $\approx 10^{13}m$, the distance the Earth travels over a year. In order to make predictions and exclusion limits, these experiments assume that the dark matter is completely smooth on these scales, with a well mixed Maxwell-Boltzmann velocity distribution [15, 16]. Furthermore, if any such small high-density clumps actually dominate the dark matter distribution in the solar neighbourhood. The indirect detection signal due to dark matter annihilation in the galaxy might also be affected.

Since existing N-body simulation of galaxy formation do not have a resolution that goes down to objects with mass as small as $10^{-6}M_\odot$, in order to address the question of the survival and impact of such microhalos we need to combine analytical estimates with the results of smaller scale simulations that can resolve such objects. The purpose of the current work is estimate the fine grained phase space distribution function of WIMPs on scales relevant to dark matter detection experiments.

Microhalo parameters and disruption processes

The dominant processes that can affect microhalos involve gravitational interactions with baryons in the stellar field during the crossing of the disk and also tidal effects of the disk potential during the orbit of the microhalo [17, 18].

As a substructure halo crosses through a stellar field, high-speed interactions with single stars will heat up the halo distribution, causing it to increase in increase its velocity dispersion and hence its scale size will also increase. This process is analogous to galaxy harassment that occurs in clusters [19] and basically has a timescale proportional to the relaxation time of the stellar disk and the time each microhalo spends within the fluctuating potential field of the stars. For an analytical estimation of this process we can use a 'distant-tide' approximation

[20], since the crossing occurs at high speed and the average distance between stars is much larger than the size of the microhalo. A single encounter between a fixed star and a microhalo moving along the z-axis yields

$$\delta \mathbf{v}_\alpha = \frac{2GM}{b^2 v_{mh}} \left(-x_\alpha, y_\alpha, 0\right), \tag{1}$$

where b is the minimal distance to the star and v_{mh} is the velocity of the microhalo. The expression $\delta\mathbf{v}_\alpha$ and the coordinates $(x_\alpha, y_\alpha, z_\alpha)$ indicate the velocity and the position of one dark matter particle with respect to the microhalo's centre of mass. Integrating the square of $\delta\mathbf{v}_\alpha$ over all stars in the field ($dN = 2\pi n b db v dt$) and taking the average over all halo particles, leads to the following growth of the velocity dispersion

$$\Delta\sigma(t) \approx \sqrt{\frac{2\pi n_*}{3 v_{mh}}} \left(\frac{2GM_* r_s}{b_{min}}\right) t^{1/2}. \tag{2}$$

Here, b_{min} is the distance of the closest encounter, n_* represents the number density of the stars and r_s is the characteristic scale size of the microhalo. Equation (2) suggests that the heating energy grows linearly with time. The microhalo disruption is complete if the total energy becomes positive. The radial expansion of the microhalo during the heating process is therefore approximately given by $\Delta r(t) \propto t^{3/2}$.

The above estimate doesn't take into account the internal structure of the microhalos, specifically how a bound system evolves as it is slowly heated. We therefore performed a simulation using a periodic box with a length of 50 pc, filled with randomly distributed stars with a stellar velocity dispersion of $\sigma = 50$ km/s and a density of $\rho = 0.04 M_\odot \mathrm{pc}^{-3}$, and explored the effect on a microhalo crossing this stellar field with a velocity of 200 km/s. This constellation corresponds to a disk crossing at the solar radius [20]. We find that 80% of the mass of microhalos will be unbound after 60 Myr (or about 30 crossings, since each disk crossing takes about $t_{dc} \sim 2$ Myr). After 80 crossings (160 Myr) even the central core disappears and the microhalo becomes completely disrupted (see pictures in Table I).

In order to determine what fraction of microhalos survive until the present day, we have to calculate orbital statistics and the distribution of disk crossing times. This can be established by tracing back the orbits of particles in a galactic potential. We use the standard Milky Way model with disk and halo particles set up by the GalactICS code [21] and we select a sample of particles in a small box around the position of the sun. The orbits of these particles are followed backwards in time and we find that the average number of disk crossings for these particles is $\bar{c} = 80$ with a standard deviation of $\sigma_c = 43$. The average crossing radius is (not surprisingly) $\overline{R} = 8$ kpc with $\sigma_R = 4$ kpc. The spread of disk crossing events for different particles follows a Maxwell-Boltzmann distribution.

We use this disk crossing distribution combined with the rate of mass loss determined from our numerical study to calculate the survival statistics of microhalos in the vicinity of the sun. Since the timescale for complete disruption in our simulation is equivalent to the average time a microhalo spends in the stellar disk, we conclude that the average microhalo in the vicinity of the sun is probably destroyed by the present time (see also [22]). But the spread in the number of disc crossings is relatively wide and a significant fraction of microhalos should still have surviving cores. Mass loss is nevertheless important: microhalos maintaining more than 20% of their initial mass should be extremely rare. Figure 1 illustrates the mass loss, where the red curve shows the disruption of a typical microhalo with 80 disk crossings at the radius of the sun.

TABLE I: *Microhalo density map at t = 0, 20, 40, 60, 80, 100, 120, 140, 160 Myr (from the upper left to the lower right). The boxlength of the images is 0.2 pc.*

However, disk crossing is not the only source of dynamical disruption. While orbiting the galaxy, a microhalo is under the constant influence of the global Galactic potential, and tidal forces will act so that the microhalo's structure becomes elongated and unbound particles will form leading and trailing tidal streams. The detailed impact of tidal streaming depend on the shape of the potential. In our simulations we use a disk potential that emerges from a density distribution of the form

$$\rho(R, z) \propto exp(-R/R_d) sech^2(z/z_d). \tag{3}$$

Here R and z are the disk radius and the height respectively, which we set to be $R_d = 2.8$ kpc, $z_d = 0.4$ kpc. The disk mass is $M_d = 4.5 \cdot 10^{10} M_\odot$.

We cannot model both heating due to stellar interactions and tidal elongation at the same time since this would require following the motion of 50 billion disk stars. We therefore performed orbital simulations for two extreme cases: an initially completely undisturbed micro-

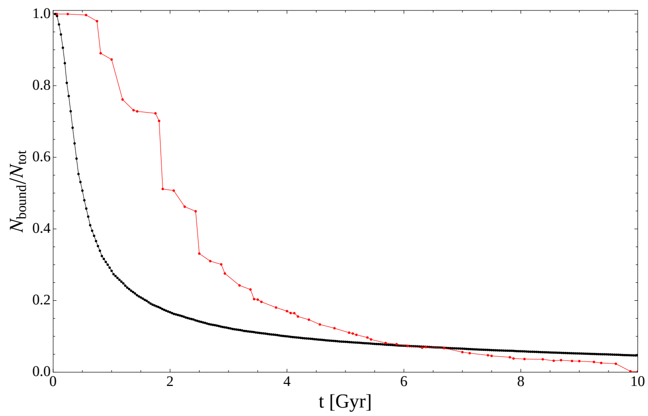

FIG. 1: *Ratio between bound and total mass of a microhalo crossing a stellar field (red) and orbiting in a Milky Way potential (black). The red curve is streched in order to simulate the effect of disk crossing on an average microhalo with about 80 disk crossings. At the beginning the mass loss via streaming is dominant but it is suppressed after about 2 Gyr. In the stellar field the mass loss is not smooth because interactions with single stars are important. An average microhalo is completely disrupted after about one Hubble time.*

halo and a disrupted microhalo with the cumulative effects of stellar heating for 160 Myr - a typical amount of time a microhalo spends in the field of disk stars.

The length of the tidal streams l due to the orbiting process can be crudely estimated with the relation $l(t) \sim \sigma_{mh} t$, where σ_{mh} is the velocity dispersion of the initial microhalo. For an initially unperturbed microhalo $\sigma_{mh} \sim 10^{-3}$ km/s, causing a stream length of roughly $l \sim 10$ pc after one Hubble time. For an initially disrupted microhalo $\sigma_{mh} \sim 10^{-2}$ km/s, and the stream length is about $l \sim 100$ pc after a Hubble time. Both length scales agree well with our simulations (i.e. see Table II).

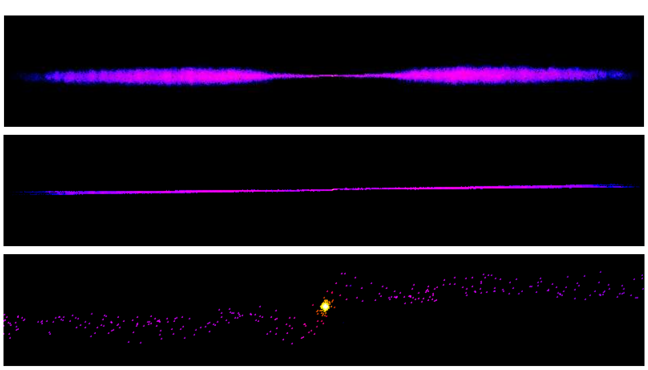

TABLE II: *Streaming microhalo after 10 Gyr in a Milky Way potential: The two images on the top show the sheet-like streams from the top and from the side (boxlength: 29 pc). The third image is a zoom in at the centre where the still bound core is visible (boxlength: 0.9 pc).*

Orbiting in the galactic potential also significantly reduces the mass of the microhalo (black line in Fig 1). After one Gyr, nearly 80% of the initial mass is unbound. However, the rate of tidal mass loss is suppressed as the tidal radius is steadily reduced. The central cusp of each dark matter microhalo has a very deep potential, as a consequence there is still a bound core with about 5% of the initial mass after 10 Gyr.

Comparing the two curves in Fig 1 leads to the conclusion that tidal streaming is the dominating mass loss process, especially at early times. However, the global tidal stripping never completely destroys the substructures - a small dense bound core remains. We find that only the interaction with single stars in the disk can eventually completely disrupt the microhalo structure, including the tightly bound inner core.

Implications for Dark Matter Detection

In direct detection experiments the differential interaction rate is sensitive to the fine grained density and the velocity distribution of dark matter particles on A.U. scales [23, 24]. Substructures like microhalos can affect the interaction rate if they are abundant enough to have a substantial likelihood of existing in the solar neighbourhood and if their density is at least the same order of magnitude as the background dark matter density in this region, $\rho_{bg} \sim 10^7 M_\odot \mathrm{kpc}^{-3}$. Equally important, the phase space for the energy deposits associated with dark matter events will not be that appropriate for an isothermal halo if a single microhalo were to dominate the density distribution in the solar neighbourhood [13, 14].

Our results above suggest that none of these conditions are generally achieved. In Figure 2 we plot the stream densities of the initially unperturbed (red) and disrupted (blue) microhalo after an orbital time of 10 Gyr. The tidal streams of the initially unperturbed halo has an average density of $\rho \sim 10^4 M_\odot \mathrm{kpc}^{-3}$, which is already negligibly low compared to the background. Only the very tiny core still maintains its initial density of $\rho \approx 10^{11} M_\odot \mathrm{kpc}^{-3}$. The initially disrupted microhalo has of course no more bound core. Its stream density is only at about $\rho \sim 10 M_\odot \mathrm{kpc}^{-3}$. The stream density of an average microhalo (with about 80 disk crossings at the solar radius) should be somewhere between these two numbers.

Thus, only a surviving core existing in the region of the earth would any effect upon direct detection. However, fewer than half of the microhalos still have bound cores because of disk crossing, and tidal effects further reduce the mass of the cores to less than five percent of their original value. We note that any substructures orbiting primarily within the disk plane would be quickly destroyed by stellar encounters.

The chance of being in such an overdense region can then be optimistically estimated: At the solar system the number density of microhalos is approximately $n_{mh} \sim 100$ pc^{-3}. Each microhalo has a volume of about

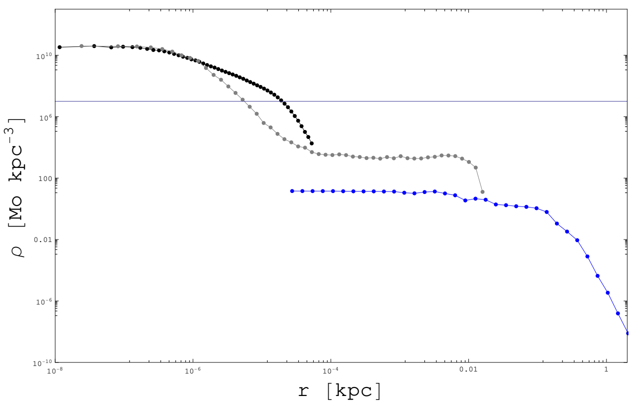

FIG. 2: *Radial densities along the tidal streams of an initially undisrupted microhalo (gray) and a disrupted microhalo (blue) compared to the density of a totally unperturbed microhalo (black). The blue straight line corresponds to the average dark matter density around the sun. After 10 Gyrs in the Milky Way potential the initially undisrupted halo still has a bound core with the same density as the unperturbed halo.*

$V_{mh} \sim 10^{-9}$ pc^3 and therefore there is a chance of about 0.0001% of being in such an overdense region. Since the interaction rate even in the center of such a region would be at most 10^4 times that expected from the background halo density, the expected mean enhancement in direct detectors due to microhalos in the galaxy is less than one percent.

The streams of particles stripped from microhalos are coherent and long, thus it is appropriate to calculate their volume filling factor. Since the stream density is $\rho \sim 10 - 10^4 M_\odot \text{kpc}^{-3}$ we expect that our solar system is criss-crossed with $f_b \times (10^3 - 10^6)$ streams, where $f_b \approx 0.1$ is the fraction of the local Galactic halo density that forms from substructures up to a solar mass. Larger substructures will be completely disrupted at the Suns position in the Galaxy due to global disk shocking and tides. The velocity dispersion within an average stream due to heating by disk stars is $\sigma \sim 10^{-2}$ km/s. Thus, the local density is determined by the superposition of a large number of independent streams, and the overall velocity distribution at the solar radius should be essentially Maxwellian, isotropic and smooth with no spiky structure, as we would assume for a smooth halo model with no substructures.

The case for indirect detection is slightly different from that described above, but not significantly so. In indirect detection experiments one tries to detect the annihilation products, such as gamma-rays, coming from the highest density dark matter regions, which is proportional to the square of the dark matter density times the volume of the region observed [26–28]. Consider a volume containing on average one microhalo $V \approx 10^{-2}$ pc^{-3}. The luminosity due to the smooth background is therefore $L_{bg} \propto V\rho^2 = 10^{-6} M_\odot^2 \text{pc}^{-3}$, whereas the luminosity of a surviving microhalo core is

$$L_{mh} \propto V_{core}\rho_{core}^2 \approx 5 \times 10^{-7} M_\odot^2 pc^{-3}, \qquad (4)$$

where we have assumed a mean core density of $10^{10} M_\odot \text{pc}^{-3}$. Thus the net boost factor due to microhalos is about 1.5, and stays below the detection limits of the FERMI experiment [29].

Finally, we consider the fine caustic sheets of particles within the Galactic halo. In the absence of fine grained heating, narrow sheets and folds will occupy regions of phase space within all collapsing CDM structures. As structures merge hierarchically, these caustic features become wrapped in phase space like a fine fabric that has been crumpled into a ball, the density at any point being preserved. During the matter dominated epoch and before structure formation the velocity dispersion of WIMPs is given by

$$\sigma_\chi \sim 10^{-10} \left(\frac{100GeV}{m_\chi}\right)^{1/2} (1+z), \qquad (5)$$

were m_χ is the mass of the WIMP [2]. Since the first structures are collapsing at redshifts $z \sim 60$, we obtain a primordial velocity dispersion of $\sigma_\chi \sim 2$ cm/s. In the outer halo these features will persist, but in the vicinity of the sun they will also suffer heating by the disk stars and become broadened in phase space and physical space.

This becomes clear if we write equation (2) as

$$\Delta\sigma = C\sqrt{t} \sim 10^{-3} \left(\frac{km}{s}\right) \sqrt{\frac{t}{Myr}}, \qquad (6)$$

where C has been determined via our simulations. For a microhalo on an average orbit we find $\Delta\sigma \sim 12$ m/s which is much larger than the primordial velocity dispersion, effectively smearing out all caustic overdensities in the vicinity of the Galactic disk.

Conclusion

As the prospects for direct and indirect detection of WIMP dark matter improve with the development of new detectors, a renewed interest in the phase space distribution of dark matter particles has arisen. It has recently been shown that hierarchical clustering continues down to extremely small mass scales, so that most dark matter currently in the halo of our galaxy may have originated in microhalos with masses as small as $10^{-6} M_\odot$. Possibly dense surviving cores, tidal streams, and caustic structures might leave phase space sparsely populated, suggesting exciting new possibilities for novel signatures that differ from the traditional experimental assumption a smooth isothermal halo. However, our results imply that tidal effects and gravitational heating effectively wipe out any such signatures for Earth based detectors. Even though we find that a significant fraction of microhalos still have a bound core today, these overdense regions are too small to be relevant for detection experiments.

The disrupted material in the tidal streams is not dense enough, by a long shot, to affect the detection signal. On Earth, there are about $7 \cdot 10^8$ dark matter particles per second streaming through our bodies (assuming $m_\chi \sim 100$ GeV), but they originate from over 10^4 streams coming from disrupted microhalos. The velocity dispersion in the streams is heated up through stellar interaction from initially 10^{-3} km/s to 10^{-2} km/s and therefore we expect an essentially smooth Maxwellian, with at most some spikes due to microhalos with an unusual orbital history [30, 31].

To summarise, our results imply that limits obtained on dark matter from detection experiments under the conservative assumption of a smooth halo with nearly Maxwellian density distribution remain valid, with a prefactor depending only on the average local dark matter density. The characterstic deviations from a Maxwellian distribution predicted from numerical simulations may be detected given sufficient detection statistics [32, 33].

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